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Bioenergy agroecosystems as a basis for food sustainability

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Abstracts. The article examines the prospects for the introduction of a bioenergy system of agricultural production in Western Polesie using the example of a reclaimed area of 10 thousand hectares, under the jurisdiction of the Shatsk Department of Reclamation Systems (Volyn region, Ukraine). A multi-option simulation of the potential sectoral structure of this region was conducted using the "Agroecosystem" software package. The study assessed the key components of the agri-resource potential of the region, identified conditions for improving its efficiency, and proposed sustainable models for sectoral development based on bioenergy principles. A comparative computer analysis showed that the most promising scenario includes organic farming, high-yield dairy production, and the processing of raw materials into dairy and meat products, oil, and flax fiber. Energy needs are met through biogas production from all agricultural waste, which is fully sanitized. The application of biological crop protection systems and energy self-sufficiency reduces production costs by 30%, while the quality and market value of high-end food products increase accordingly. As a result, agricultural profitability rises significantly, and the local population benefits from affordable, high-quality food and products made from natural raw materials. In the future, an important part of the profit could come from reducing greenhouse gas emissions.

Keywords: agrosphere, organic food products, bioenergy agroecosystems, sectoral structure, profitability, greenhouse gases.

1 Introduction

The modern stage of human development is characterized by a significant increase in environmental impact. This predominantly has a negative effect on the ecological state due to air, water, and soil pollution. Furthermore, these processes are accompanied by

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significant climate changes, particularly global warming. This, in turn, leads to the intensification of various degradation processes, posing serious threats to the agrosphere, biosphere, anthroposphere, noosphere, and to the nature of the Earth as a whole. Therefore, before reaching the point of no return, it is necessary to transform the technosphere to neutralize its destructive impact on the planet's natural processes. A balance must be achieved between the biosphere and the technosphere. This must take into account the specifics of all major sectors of the economy: transport, construction, industry, energy, and agriculture. The latter two components have the potential for accelerated improvement. These opportunities are based on the process of photosynthesis or the biological accumulation of solar energy in the form of organic matter. In crop production, it is primarily necessary to create optimal conditions for the active binding of atmospheric carbon and nitrogen by crops and soil microorganisms. Rational, balanced distribution of the obtained biomass between food, bioenergy, technical raw materials, and fertilizers ensures bioenergetic agroecosystems. Their widespread implementation in agricultural areas will solve many problems in the agrosphere, biosphere, and technosphere from the perspective of fully providing production processes with renewable energy, achieving ecological and social well-being.

2 Materials and Methods

The modern stage of human development is characterized by an increased impact of its activities (technosphere) on the climatic and ecological state of the planet [1-3]. This, in turn, inevitably quantitatively and qualitatively affects the noosphere, anthroposphere, and biosphere as a whole [4-6]. Such threats require the development of an effective system for operational and strategic planning of sustainable development pathways for humanity, ensuring environmental cleanliness and climate stability [7,8]. The only solution is the systematic formation of a balance between the biosphere and the technosphere [9,10]. Such a system must take into account the specifics of all major sectors of the economy: transport, construction, industry, energy, and agriculture [11-13]. Compared to other areas, the latter two components have the potential for accelerated and radical increases in ecological and economic efficiency. A comprehensive solution to the tasks set before these sectors is largely determined by the replacement of a significant portion of traditional fossil energy resources with alternatives [14]. In the agrosphere [15], this issue is mainly addressed by intensifying the biological binding of atmospheric carbon and nitrogen (photosynthesis [16,17], nitrogen fixation [18,19]), increasing the level of recycling of useful mineral elements [20,21], improving the phytosanitary condition of agroecosystems by implementing biological plant protection systems [22,23], and ensuring energy self-sufficiency [24,25]. As a result, the costs of energy-intensive chemical-technogenic resources in production are minimized, the cost of food is reduced, and its quality and price are increased [26,27]. Bioenergy agroecosystems ensure sustainable food production by reducing dependence on chemical fertilizers and fossil energy resources. The use of organic fertilizers and renewable energy sources helps to increase soil fertility, reduce greenhouse gas emissions and create environmentally friendly products, ensuring food sustainability. Computer modeling was used with the following stages of work:

- Setting a specific task, describing processes and systems, forming the research methodology.
- Formalizing the task, building its mathematical model.
- Checking and correcting the model, determining its adequacy to real conditions.
- Searching for an optimal solution to the task based on the refined model, building an algorithm for its processing.

- Creating a computer program to implement the algorithm's capabilities and conducting a computational experiment to obtain a set of data describing the main processes, technologies, and other components of agroecosystems.
- Analyzing the obtained results, bringing them to the necessary substantive form, and their practical application.

The effectiveness of the developed models was evaluated based on the information from regional stationary agrotechnical experiments and typical production systems with different levels of resource and energy provision. This allowed for the formation of an understanding of the overall direction of energy and material flows when implementing the model in practice, as well as the expected levels of economic and ecological-energy efficiency of agroecosystems. An analysis of the agri-resource potential of the main contrasting agricultural areas of Ukraine was conducted. Based on the results, scenarios for the development of regionally adaptive models of agroecosystems were developed, and a comprehensive assessment of the feasibility of their implementation was provided. In particular, in the context of global warming, special attention was given to the most productive and resilient reclaimed lands. Pre-project research was conducted in the northwestern part of the Volyn region of Ukraine, within the Pripyat River basin. With the agreement of local government authorities, 10,000 hectares of arable drained land were allocated for the bioenergy agricultural production system. Thus, the research object is a reclaimed area that includes 13 reclamation systems managed by the Shatsk Drainage Systems Administration within the former Shatsk and Liuboml administrative districts of the Volyn region. Multi-variant simulation computer modeling of promising options for agricultural production development in this area was carried out using the "Agroecosystem" software package.

3 Results and Discussions

Using an example of a reclaimed area of 10,000 hectares managed by the Shatsk Drainage Systems Administration (Volyn region), the prospects for implementing a bioenergy agricultural production system in Western Polissia are demonstrated. Multi-variant simulation computer modeling of promising options for the sectoral structure in this area was carried out using the "Agroecosystem" software package. An assessment of the components of the agro-resource potential of this region was conducted, conditions for increasing the efficiency of its use were outlined, and prospective models for the development of the sectoral structure on a bioenergy basis were proposed. Comparative computer analysis showed that the most attractive option includes the following components: organic farming, high-yield dairy cattle breeding, processing of raw materials into dairy and meat products, oil, and flax fiber. The system's energy needs are met by processing all waste in a biogas plant where they are completely decontaminated. Almost all the macro and microelements removed by the crop are returned to the soil with the digestate. Along with optimal crop rotation in crop rotations, this allows for the transition to organic production using a biological plant protection system. Due to the minimization of agrochemicals and the use of self-produced energy, the cost of the obtained products will be 30% lower than the baseline, and the selling price of high-quality food products will accordingly increase. As a result, the profitability of agricultural production will increase by two orders of magnitude, and the population will be provided with affordable food of the highest quality and goods made from natural technical raw materials. In the future, an important part of the profit may come from reducing greenhouse gas emissions.

The goal of the research was to justify and implement energy-independent, climate-neutral, highly profitable organic agroecosystems that ensure balanced production of bioenergy, high-quality food products, raw materials for industry, and fertilizers. These systems are formed by creating a series of production cycles where the waste from one component serves as valuable raw material for the next. The main advantage is that the end products are fats, proteins, carbohydrates, and hydrocarbons. With these, only hydrogen, carbon, oxygen, and nitrogen, which are part of the planet's atmosphere, are removed from the agroecosystems in the form of organic compounds. Mineral substances taken from the soil by plant biomass are used repeatedly in a closed cycle with organic fertilizers (digestate). In this process, a large portion of soil carbon and nitrogen is also recycled. Methane fermentation completely sterilizes all waste, including destroying weed seeds, which lose their ability to germinate. This is important because it prevents the spread of unwanted plants and reduces the need for herbicides. Combined with optimal crop rotation in crop sequences, this allows for the transition to a biological plant protection system in the long term. Ultimately, minimizing the use of agrochemicals and industrial energy will not only allow the transition to organic farming with corresponding benefits but also reduce the cost of the final products by 25-30%. The successful achievement of the set goal is possible under the condition of solving the following tasks:

- Formation of infrastructure that allows for the most efficient use of the agro-resource potential of agricultural areas;
- Ensuring rapid payback of financial investments through energy self-sufficiency and minimizing the use of chemical-technogenic resources;
- Development of organic farming systems to obtain affordable high-quality food products;
- Ensuring extended reproduction of soil fertility and sustainable increase in the productivity of agricultural lands;
- Reducing the carbon footprint and minimizing greenhouse gas emissions;
- Achieving stable ecological balance with parameters close to the natural local conditions;
- Creating comfortable living conditions for the population.

The set goals were achieved by developing the following directions: analyzing the features of regional hydrothermal conditions and the dynamics of their changes; substantiating the use of water and other reclamation methods; assessing the bioproductivity and efficiency of the current most widespread practices of agricultural land use; modeling various combinations of the most productive and profitable crops in crop rotations; justifying the distribution of plant biomass between bioenergy, food, industrial raw materials, and fertilizers to ensure the desired ecological, economic, and social outcomes; conducting multi-variant computer simulation modeling of the future production system structure based on comprehensive economic, energy, environmental, and social assessments to identify the most appropriate development directions; implementing the chosen model in practice. Implementation conditions: strengthening systemic state policy in the field of alternative energy development and organic agricultural production; extensive use of information systems; developing organizational schemes adapted to regional conditions for forming bioenergy production structures; creating experimental operational agricultural enterprises; short payback period for financial investments; availability of significant investment resources.

Depending on productivity, one hectare of agricultural land (arable land) can support up to 3 conditional head (c.h.) of livestock, and on reclaimed land – up to 4 c.h. Approximately half of the sown area should be allocated to grain crops, and half to forage crops. To ensure high productivity of livestock, concentrated feeds must be well-balanced in proteins and fats. Therefore, about 50% of the grain area needs to be allocated to grain legumes (soybeans, etc.) and oilseed crops (sunflower, rapeseed, etc.), from which meal and oil are produced. In turn, about half of the crops in the forage group are allocated to silage crops (corn, sorghum, etc.), and the other half to perennial and annual grasses for hay and haylage (alfalfa, clover, etc.). It is important that with such a structure of sown areas, a crop rotation is formed with a near-optimal sequence of crops (marked as number 1 in Figure 1). The infrastructure must include a grain storage facility (2) and storage facilities for main forages: hay, haylage, silage, and straw (3). In the sugar beet growing zone and on irrigated lands, it is advisable to allocate 20-25% of the sown area to this crop. With modern technologies for storing root crops for 9-10 months and their gradual processing at a sugar factory (4), a significant portion of silage in livestock feeding rations is replaced by fresh pulp.

On the high-quality compound feed production line (5), crushed grain (wheat, barley, corn, etc.), meal (soybean, sunflower, etc.), milk and meat processing by-products (whey, meat and bone meal, etc.), molasses, and other feed additives are mixed. The process of producing oil and meal can be supplemented with equipment for producing biodiesel (6) if necessary. Currently (03.05.2024), 1 ton of sunflower oil is sold for 840 USD, and 1 ton of diesel fuel is sold for 1350 USD.

Next, the main feeds from the storage facilities and concentrated feeds from the feed mill are delivered to the livestock complex (7). About 40% of the dry matter is used to maintain the animals' vital functions and ultimately transforms into food products (8) and by-products (CO2 from respiration, manure, etc.). All waste is processed at the biogas plant (8), where approximately half of the biomass is transformed in the methane fermentation reactor into biogas (60% methane), and half into digestate (non-decomposable residue). This organic fertilizer retains up to 30% of the organic carbon bound as a result of photosynthesis to replenish the mineralized soil reserves. It also accumulates almost all the macro- and microelements removed from the soil. The biogas is usually burned at a co- or trigeneration power plant, producing "green" electricity, heat, or cold depending on the season (9).

It is evident that the bioenergy agricultural production system will be quite complex to manage. First and foremost, it is extremely important to ensure the balanced operation of all its components, as disruptions in synchronization will reduce the efficiency and profitability of production activities. A corresponding computer system is designated for managing such a complex (10). Technical raw materials and organic food products, which consist of atmospheric components (carbon, nitrogen, oxygen, and hydrogen), are put up for sale (11).

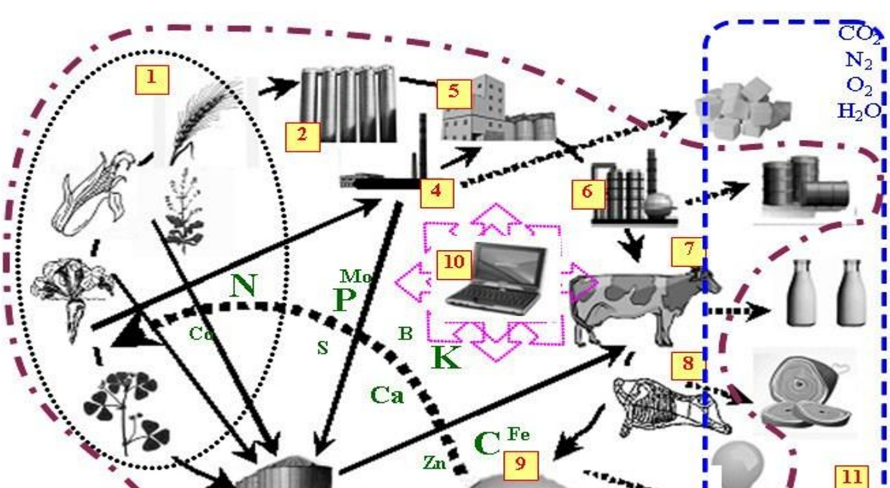

Fig. 1. Scheme of bioenergy agroecosystem.

The average precipitation in the Western Polissia region from 1991 to 2023 relative to the norm (1961-1990) has not changed. At the same time, the average annual air temperature has increased by 1.2°C, and as a result of warming, evaporation has intensified. Consequently, in this area, the water balance has deteriorated in certain months. The number of years with insufficient moisture is 27% in May, 47% in June, 60% in July, and 73% in August. Moreover, in the last 3-4 years, there has been not only an increase in temperature but also a trend towards a decrease in precipitation during the growing season. All this indicates the need for modernization of existing reclamation systems to reliably regulate the water-air regime of drained lands throughout the entire growing season.

Long-term studies in agrotechnical experiments show that the natural fertility of drained lands provides an average of 4-5 feed units per hectare. With the optimization of moisture conditions, nutritional regime, and crop composition in the structure of sown areas, the productivity of crop rotations can reach 14-16 feed units per hectare.

The analysis of various scenarios for the development of agricultural production on reclaimed lands in the Western Polissia region has identified one of the priority areas for improving the production structure (Fig. 2). This involves, alongside food and bioenergy, the production of technical products required on the market for natural fiber goods. Modeling has shown that for these conditions, a structure of sown areas close to optimal is: 20% flax, 30% cereals, and 50% forage crops. This allows for an annual yield from 10,000 hectares of reclaimed land of up to 5,000 tons of flax fiber, 270,000 tons of fresh forage biomass, 30,000 tons of straw, and 25,000 tons of high-quality compound feed, with the potential to support up to 2 conditional heads of high-performance dairy cattle per hectare. With the appropriate infrastructure, such a raw material base would provide an output of more than 5,000 tons of cream, up to 7,000 tons of hard cheeses, more than 1,000 tons of beef and veal (bone-free), 2,600 tons of oil, and up to 3,000 tons of flax thread and twine. The bioenergy complex with a power plant is designed to handle 70,000 tons of waste (in dry matter) and produce 14 million cubic meters or 1,400 cubic meters per hectare of methane.

Organic fertilizers will accumulate in a volume of 40,000 tons of dry matter, or 16 tons per hectare, equivalent to manure of standard quality. With the digestate, 85% of nitrogen, 95% of phosphorus, and nearly 100% of potassium and micronutrients will be returned to the soil from the harvested crop. This, combined with biological nitrogen fixation (70-100 kg/ha) and organic carbon and nitrogen from fertilizers and plant residues (3 tons/ha), will ensure the extensive restoration of soil quality and fertility, as well as its energy potential.

Modeling showed that creating a balanced infrastructure of this scale would require an investment of 130-140 million USD. The production and sale of the planned range of products will generate gross income at the level of 130 million USD. Considering production and overhead costs, as well as payments for VAT and land lease (30-40 million USD), the net profit would amount to 90-100 million USD, with a payback period for capital investments of 2-3 years. Achieved profitability will enable further active development of this system using own funds (Table 1).

Expanding this practice to all 3.2 million hectares of drained lands in Polissia would allow for an annual production of 4-5 billion cubic meters of biological methane and would provide a net profit of 30 billion USD each year.

In 2019, the cost of greenhouse gas emission quotas on the European market was 10 euros per ton of CO_2. By 2021, it had risen to over 50 euros per ton and is expected to reach 100 euros per ton by 2030. The operation of the bioenergy production system, compared to the current widespread practice of grain production, significantly reduces CO_2 and N_2O emissions into the atmosphere in the following ways:

- Repeated use or recycling of biogenic elements reduces fossil fuel consumption for the production of industrial mineral fertilizers and decreases CO_2 emissions by an average of 4 tons per hectare.
- A significant share of leguminous crops in the sown area structure ensures the accumulation of 70-100 kg/ha of biological nitrogen, which also contributes to reducing fossil energy use for mineral fertilizer production.
- Depending on the productivity of land after processing livestock and other waste, the output of methane from a biogas plant per hectare will range from 2,000 to 2,500 cubic meters.
- The production of vegetable oil can be up to 200-300 liters per hectare, corresponding to a reduction in CO_2 emissions from burning the same amount of petroleum products.
- Annual carbon sequestration resulting from the humification of root, post-harvest residues, and applied organic fertilizers can reach up to 0.25 tons per hectare.

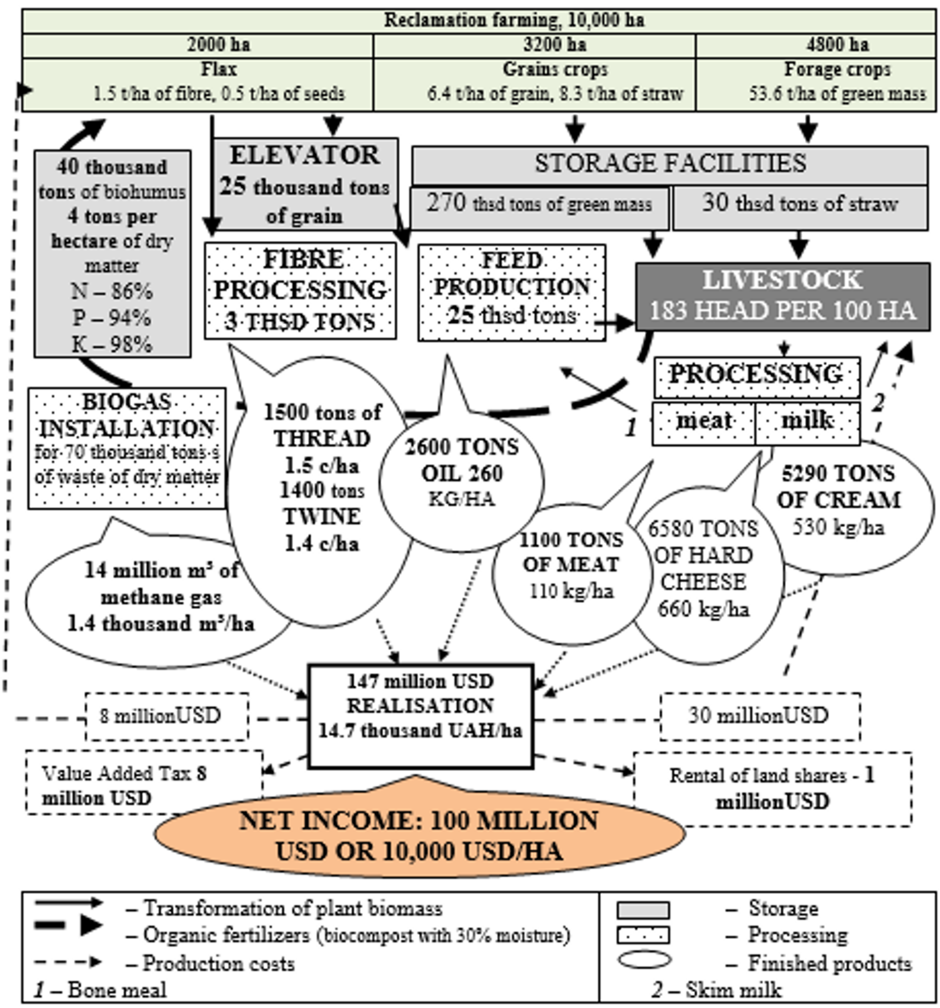

Fig. 2. Model of bioenergy system of agricultural production for reclaimed lands of Western Polissya.

- Approximately 15% of the nitrogen from mineral and organic fertilizers applied to the soil is lost in gaseous form, with nitrous oxide having a greenhouse effect 300 times stronger than CO_2. This needs to be considered when reducing the use of industrial fertilizers in bioenergy systems.
- Overall, greenhouse gas emissions can be reduced by 15-20 tons per hectare when calculated as CO_2.

Table 1. Expected economic indicators.

Indicator	Units of measurement	Quantity	Amount, million USD
INFRASTRUCTURE			
Mechanisation of crop production	thous. ha	10	5
Elevator	thousand tons	20	1
Livestock complex	thousand heads	24	26
Breeding stock	thousand heads	8	16
Milk processing	thousand tons	80	7
Meat processing	thousand tons	3	1
Bioenergy complex	thousand tons (dry matter)	70	20
1	2	3	4
Fibre and twine production	thousand tons	3	20
Warehouses for products	thousand tons	16	1
Storages for feed	thousand m^2	20	2
Storages for digestate	thousand m2	14	2
Modernization of land reclamation systems	thous. ha	10	35
Capital expenditures, million USD			**135**
PRODUCTION			
Electricity	million kWh	60	10
Heat energy	thousand Gcal	72	3
Meat	thousand tons	1,1	6
Hard cheese, 30%	thousand tons	6,6	51
Cream, 20%	thousand tons	5,3	23
Canvas	thousand tons	1,5	29
Burlap	thousand tons	1,4	8
Ammonium nitrate	thousand tons	3,3	1
Superphosphate	thousand tons	2,7	1
Potassium chloride	thousand tons	2,8	1
Gross profit, million USD			**135**
PRODUCTION COSTS			
Flax cultivation and fibre processing			5
Operation of land reclamation systems and bioenergy complex			1
Animal husbandry			11
Milk processing			5
Processing of live weight of culled cows and calves			1
Overheads, VAT, payments for shares			12
Technological costs			**35**
Profit			**100**
Payback period of capital expenditures, years			**2**

**Economic benefits from selling the products as organic and potential revenues from greenhouse gas emission credits have not been considered.*

Thus, the development of reclaimed areas in the Polissia region of Ukraine based on bioenergy agricultural production principles would allow, within a single technological complex, to annually produce approximately 1,500 cubic meters of methane gas per hectare, 1.3 tons of meat and dairy products per hectare, 0.3 tons of plant fiber per hectare, up to 0.3 tons of oil per hectare, and 4 tons of dry matter organic fertilizers. This approach creates an optimal balance of macro- and micronutrients without using industrial mineral fertilizers, adopts biological plant protection systems, minimizes the use of agrochemicals, and transitions to organic farming principles, reducing production costs by 30-35%. At the same time, it is anticipated that the systematic enhancement of soil fertility will steadily increase crop productivity while improving the region's ecological condition. The profitability of production activities could reach 10,000 USD per hectare, enabling a territorial expansion of the bioenergy system by 20-25% per year and ensuring comfortable living conditions for the local population. This agricultural production model can be practically implemented by forming an association of land users within the reclamation systems.

4 Conclusions

- **Multivariable simulation modeling** enables the development and implementation of advanced agricultural production systems for the rational use of the agrarian resource potential of any agricultural territory. This potential includes agroclimatic, soil, water, biological, chemical-technogenic, and other resources. Balanced utilization of these resources allows for achieving desired economic, ecological, and social results in Ukraine's agrarian sector.
- **From the perspective of significantly increasing efficiency**, it is important to organize the production structure such that the waste from each component becomes valuable raw material for the next. A closed, sealed cycle of biogenic elements is purposefully formed according to the specific conditions. Primarily, it is necessary to minimize non-productive losses of carbon and nitrogen. Meeting these conditions allows for balanced production of energy, technical raw materials, fertilizers, and organic food without the use of agrochemicals.
- **Minimizing the use of industrial energy and resources** will ultimately result in a substantial reduction in production costs while maintaining high quality. On the other hand, it will achieve a sufficient level of system independence from external, particularly adverse factors and influences. Important aspects include improving the environmental status and creating comfortable living conditions for rural populations.
- **The implementation of bioenergy systems in agricultural production** achieves profitability at the level of 5-7 thousand USD per hectare, and more than 10 thousand USD per hectare on reclaimed lands. This ensures a high level of local employment with decent wages. After fulfilling investment obligations, there is an opportunity to refine and expand the system territorially using own profits. Compared to traditional or current widespread production practices, direct and indirect CO_2 emissions will be reduced by 15-20 tons per hectare.
- **The implementation of the bioenergy system in agricultural production** should be based on creating associations of land users, in this case, within the reclaimed territory.

- **With widespread use of bioenergy approaches** in the agrarian sector, the contradictions between the technosphere and the planet's biosphere will be significantly less acute.

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